

**The Green House Effect:
Designing a Sustainable House for the Middlebury College Campus**

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“Buildings are responsible for more external pollution than any other product. About half the greenhouse gases produced each year by industrialized countries are related to buildings, through the use of energy” (Mackenzie, 1991).

INTRODUCTION:

Of the myriad environmental issues concerning the fate of Earth, fossil fuel consumption is perhaps the most urgent. Every day oil and coal fired power plants continue to eat away at our dwindling natural reserves, and the pollution from this industry both alters the global climate and compromises the health of natural communities. Yet amidst this impending crisis, few have yet to take direct and remedial action. Is it because we are ignorant of the problem? Are we unwilling to give up our consumptive lifestyles? Or are we simply unaware that viable solutions exist?

This paper seeks to address one solution -- environmental engineering, which is the science concerned with designing and constructing sustainable buildings. Since buildings are responsible for half the greenhouse gases produced each year by industrial countries (Mackenzie, 1991), environmental engineering seems a logical and prudent starting-place from which to examine the problem. Additionally, rather than investigate global applications, we focus on the aspects of environmental building design that are relevant to Vermont, and ultimately come up with a proposal and general plan for a new environmental house on the Middlebury campus. The success of the Environmental

Studies program and the distinct lack of environmentally sound architecture on campus certainly justifies such a project.

In order to make a recommendation for the design of house on Middlebury's campus, we examine the basic design principles of an energy-efficient house. We begin with a discussion of efficient building materials that can be substituted for less efficient materials that are energy intensive to manufacture. Second, we discuss the benefits and properties of passive solar design to reduce the energy needed for space heating are discussed. Then we assess alternative sources of energy that could be created on-site of the proposed environmental house. We then examine various case studies to show the variety of architectural designs to reduce residential energy consumption. Finally we conclude with our proposal for a house on campus with a discussion of how it functions and how much energy is being saved.

BUILDING MATERIALS:

Sustainable architecture involves a commitment not only to the self-sufficient functioning of a home once built, but also a more holistic view of the structure and its environmental impact throughout its entire lifespan. This lifespan begins with the materials that go into its construction. Therefore, we commence our project with an investigation into the various building materials available to us in the construction of a sustainable house on the Middlebury campus, and an assessment as to their environmental properties.

First, a consideration of the production of these materials is necessary, including the amount of energy required for the manufacturing process, the production of hazardous

or polluting byproducts as a result of this process, whether or not the products are yielded or created in a sustainable manner, and the potential for reuse or recycling of the material after use. These characteristics must then be considered in light of the material's practicality in achieving the purposes of a sustainable house and existing in a harsh Vermont climate. Attributes such as insulation abilities, durability, maintenance, aesthetic value, and expense need to be considered.

Concrete is one material that is integral in architecture, forming the foundation of the majority of buildings, as well as the exterior structure of many. Concrete is a mixture of cement, water, sand, and gravel or crushed rock. While cement comprises only 10-20% of the compound, the process that produces cement is highly energy intensive, accounting for 94% of the total energy input for concrete production (Steele, 1997). The energy is used to fuel a rotating kiln, which heats up the component limestone and clay, catalyzing a chemical reaction in which the limestone calcinates into lime. This chemical process results in the During this process, the kiln reaches temperatures of up to 2700°F. This heating, in conjunction with mining and transport of the finished cement, requires on average 6 million BTUs per ton of cement (Steele, 1997).

The high energy input required to manufacture cement reduces its (and subsequently concrete's) sustainability with respect to energy efficiency. The fossil fuels used in all elements of production (including firing the kiln and transportation) are nonrenewable on a human time scale. In addition, the modern world's high level of consumption is causing the fossil fuel reserves to be depleted rapidly. Therefore, concrete, by way of its constituent parts, comes from an unsustainable source.

Moreover, the use of fossil fuels in production has environmental impacts in terms of greenhouse gas emissions. 60.8% of the fuel required to produce cement comes from the burning of coal; indeed, close to 250kg of coal are burned for each ton of cement (Steele, 1997). Coal combustion results in the release of the gas CO₂, which is also produced in the chemical alteration of limestone in the kiln. In total, production results in the emission of 9.8 million metric tons of CO₂ for every 76 million metric tons of concrete (Steele, 1997). This has serious consequences for global climate change due to the fact that carbon dioxide is the largest anthropogenic source of climate change.

Apart from its environmental impacts, however, concrete has many advantages as a building material. The substance can be constructed fairly quickly, has a very long life span, and requires little maintenance. Concrete is also fire-resistant, which is a draw for many builders. Lastly, concrete has a high thermal mass, which is ideal for those utilizing passive solar design.

Whereas concrete is formed rather rapidly, steel production entails a lengthy, complicated process that is even more energy intensive than concrete. Steel is produced with iron ore, limestone and coal. The iron ore is extracted using open pit or shaft mining techniques. Limestone is also removed through open pit mining processes. After removal through blasting, the limestone is crushed and sized. Coal is extracted, crushed, sieved, and heated to form the substance known as “coke.” Coke is simply coal removed of all volatile gases. The three ingredients are then fed into a furnace where the iron ore is heated to a molten state and combined with the limestone and coke, producing steel.

This process is so energy intensive because each component requires its own production of a sort before it is ready to be combined in the end. The standard amount of

energy required in the production of building materials is 580 watts/ton, the average amount required for timber production. In comparison to this, steel production requires *twenty-four times* the average amount of energy; whereas concrete formation consumes only five times the average amount (Harland, 1993)!

Once again, this process is a drain on fossil fuels reserves as well as a contribution to global climate change. In addition, pit mining is an extremely wasteful practice, requiring the extraction of five times the amount of material needed to glean the desired quantity of ore (Steele, 1997). Furthermore, it leads to erosion, dust, and toxic runoff. Despite the high level of degradation incurred through steel production, the building industry is still the largest consumer of steel worldwide (Steele, 1997). Why? As Steele points out, “the manufacture of steel has become one of the most important indicators of the economic prowess of an industrialized nation” (1997). The desire to appear modern and advanced can lead one to turn a blind eye to ecological considerations.

Timber may be the most ‘environmentally friendly’ building material. Without costly heating processes, the energy costs of timber production are incurred mainly through the felling, sawing, treating, and transportation of logs, which does not add up to the large energy expenses of concrete or steel. Timber is also recyclable and biodegradable, and has a very high strength-to-weight ratio, which speaks to its durability. Once assembled, timber requires little or no maintenance, making for a convenient material. In addition, wood is an excellent insulator, providing fifteen times the insulating power of concrete (Coffee, 1981).

One must still be careful when selecting timber for a home, however. When the wood originates in a tropical forest, for example, chances are that the timber was *not*

forested sustainably, as, according to the International Tropical Timber Organization, less than 0.2% of tropical hardwoods are managed in a sustainable manner (Harland, 1993). This tropical hardwood is also often a component of plywood; therefore, it is important to always be aware of the source of *all* parts of a material to ensure purchasing in an ecologically conscious manner.

Brick is another popular material used in home construction. It consists of the blending of three raw materials: surface clays, shale clays, and fire clays. The clays that are not already particle-sized (such as shale) are crushed, and then the three substances are placed in a kiln for drying, at temperatures between 2900°F and 3600°F. As seen before, this process requires massive energy inputs to sustain such high temperatures. Moreover, a large amount of the energy consumed in heating the kiln is simply wasted due to poor kiln insulation. This can be avoided and kiln efficiency can rise through the incorporation of better insulation, such as the addition of a heat-trapping sleeve that fits around the kiln, as well as heat-recovery techniques that ‘recycle’ heat.

Besides wasteful kiln firing, brick production also results in the creation of toxic gases and vapors, such as carbon monoxide, volatile organic compounds, and particulate matter. When released, these gases are both corrosive and polluting. The emission of such vapors can be reduced through the selection of raw materials that together produce the least amount of toxic gases. Lastly, one must also be aware of the extraction processes used to obtain the clays and whether or not it is wasteful and/or destructive to natural habitats and groundwater.

Finally, slate is yet another building material widely utilized. This strong, durable, long-lasting material can be recycled many times before becoming unusable. Slate is

abundant in the natural world, but is nonrenewable; therefore, perhaps use in moderation is most appropriate. A major drawback to the use of this metamorphic rock is the initial cost, which can range from \$200 to \$1200 per square foot (Harland, 1993). The reason for most of this cost is the amount of labor required to extract the slate. Once again, consumers should be aware of the methods of extraction employed in order to choose a material that results in as little environmental degradation as possible.

PASSIVE SOLAR DESIGN:

We know that much of the fossil fuels burned nowadays go into producing energy for the heating of buildings. The majority of the energy consumed by a house is used for space heating. A large part of this gets squandered by poorly designed houses. To add insult to injury, we completely neglect the possibilities for collecting free energy from the sun. Taking advantage of what the sun offers freely could greatly reduce the amount of fossil fuels we burn for heating.

Two considerations should be kept in mind while designing a house, which uses as little fossil fuels as possible for space heating. First, one must use a non fossil fuel energy source to produce heat. Second, one must design a house, which holds the heat produced in the most efficient way possible.

Attention to the design of a house in order to harness the energy of the sun can meet most home heating needs. Designing a house to absorb and store the energy provided by the sun is known as passive solar architecture. Numerous examples of passive solar architecture exist between the latitudes of 22-56 degrees where at least 70-80% of a home's heating needs have been provided for by the sun alone (Mazria, 1979). There are three

basic designs for passive systems that can be used to accomplish this. These systems are direct gain, indirect gain, and isolated gain.

In direct gain systems, the sun heats the living space by making it the actual solar collector. Such a house includes large expanses of south facing double glazed windows. These windows must face as close to south as possible to take full advantage of the sun's strongest energy. Ideally, they will be angled to maximize the amount of low angle winter sunlight and minimize the amount of high angle summer sunlight. The way this system works is that solar radiation passing through the southern windows heats both the space and a thermal mass within the room. Enough heat must be trapped in a thermal mass to be radiated back into the space when solar energy is no longer heating the space directly such as on cold winter nights. Both the floors and the walls of the space must be constructed of materials capable of storing heat. The most common materials for a thermal mass are concrete, brick, stone, adobe or stored water. The advantage of this system is that it can work well even in cloudy climates where the solar energy is more diffuse (Mazria, 1979).

The second system is known as indirect gain. The energy from the sun strikes a thermal mass situated between the living space and the solar collecting windows. The heat stored within the thermal mass then radiates back into the space. When heat is not wanted, curtains can be drawn across the thermal mass to prevent it from entering the space directly. Two techniques for indirect systems are thermal walls and roof ponds. Thermal walls use a south-facing wall of glass with a thermal mass placed 4 inches behind the glass. These walls can be made out of any material that works well as a thermal mass. Some popular choices for thermal walls are cement and 50 gallon drums of water stacked on top of each other. The second popular type of indirect system is known as roof ponds. These

are enclosed bags of water placed in the roof to absorb the heat of the sun. Some drawbacks for these systems include the high degree of structural integrity of a building necessary to support roof ponds. Usually, roof ponds require steel I-beams for support (Mazria, 1979).

Isolated gain systems use thermal storage units that are isolated from the living space. Heat can be drawn from these thermal storage units as needed. These units may be large containers of air or water placed adjacent to a solar collector. By taking advantage of the fact that hot air rises, convection loops can be set up where the hottest air or water in the containers is always made available and the coldest air is always sinking back towards the solar collector to be reheated.

Another element of an isolated gain system can be an attached greenhouse. The sun heats the air in the greenhouse as well as a thermal mass placed on the north wall. This thermal wall acts as a divider between the living space and the attached greenhouse. Heat from this thermal wall can transfer itself into the living space while also radiating back into the greenhouse to keep it warm during the night (Mazria, 1979).

The advantage of passive solar systems is that from the day of installation they proceed to work with just about no human attention. They have no moving parts, and therefore require little maintenance. Because they are part of the overall design of the house, they require no more cost than the initial amount to build the house. Passive systems make use of a clean and free energy source. As such, they are a great alternative to fossil fuels.

The second large component of heating a house involves retaining the heat produced in the most efficient way possible. Two major means for accomplishing this feat exist. The first is to put the house underground where it will be exposed to only the heat

stresses of a much milder climate. The second option is insulating the house as well as possible such as the method taken within super insulated houses.

In an underground house, 3 sides of the house can be buried within the earth. The southern side of the house remains exposed to allow for passive solar input. Eight feet below the ground during a Vermont winter can be up to 70 degrees F warmer than the air at the surface. This translates to exposing the house to a climate more along the lines of that experienced in Georgia or Alabama during the winter than that of Vermont. In such cases, the house only needs to be insulated against the more moderate climate experienced underground as opposed to that which exists above ground. The ideal site for an underground house is a slope of 1 to 5 or 1 to 6. The slope should allow for the house to face somewhere within 15 degrees of due south. The house should be buried deep enough for vegetation to grow above. Planners of such a house should also be aware of the water table depth to make sure that the house can be buried to the desired depth. Furthermore, all aspects of the house must be waterproofed sufficiently (Metz, 1981).

In a super insulated house, the R-values for insulation are increased from R 20 in the walls to at least R 40 and from R 30 to R 60 in the roof. This provides for a house where the heat energy generated from human bodies, light fixtures, and appliances are adequate to heat the house. It also means that the tight seal of the house prevents much air from penetrating from the outside. This allows most of the heat generated to remain within the building; however, it can also create a very stagnant and unhealthy environment (Metz, 1981).

After a review of the buildings in the area that incorporate passive solar architecture in their design and a review of the literature, our general recommendation is that a house in

Vermont should take advantage of passive solar design when possible. Since passive solar is not always 100% efficient or where obstructions may prevent clear exposure to sunlight, an auxiliary wood stove can provide a secondary means of heating the structure since wood in Vermont is sustainable, easily accessible, and cheap. Depending on design and site considerations such as economics and aesthetics, various aspects of underground housing and super insulation could also be considered.

Besides just setting up a passive solar system to utilize the energy produced by the sun, a number of ideas can be incorporated into a building that will allow the system to work more efficiently as well as reduce the amount of heat loss. The following are some of the details of more traditional housing design, which should be considered. First, the house should attempt to reduce its surface to volume ratio to minimize heat loss. Geodesic domes are the best way to reduce a buildings surface to volume ratio. If this is not possible for aesthetic or design purposes, a house should attempt to be a consolidated shape such as a cube where no parts of the building will stick out like lonely appendages. Structures that jut out create a greater surface to volume ratio and are often farther removed from the heat source.

In order to take advantage of the maximum amount of solar energy and minimize the amount of northern exposure, the house should follow the principles of a saltbox houses in New England. The small northern wall should have only small if any windows while the southern wall should have as many windows as possible since southern facing windows show a heat gain in most northern latitudes (Mazria, 1979). If possible, the house should be elongated on an east/west axis in order to allow for a large amount of southern exposure.

Since the heat from the sun will be strongest on the southern side of the house in

passive solar designs, certain aspects should be considered in planning the house. In designing the layout of the house itself, the warm southern side of the house should be used for spaces that will be inhabited often. Living rooms, kitchens, and family rooms should be placed there. The colder northern side should be used for areas that do not require as much heat. Good uses of the northern space include hallways, closets, storage, stairways, and corridors. Bathrooms could also be placed on this side or on the east or west walls.

Attention should be placed to prevent heat from escaping from openings in the buildings. All windows should be made from the most energy efficient glass possible. Windows can also be recessed from the wall to reduce heat loss through convection. All entrances should be protected in some way from prevailing winter winds. Having some sort of airlock at the entrance prevents cold winds from penetrating the core of the house. Woodsheds, or mudrooms with a door leading into the rest of the building that is kept closed can accomplish this purpose.

One of the most important things to consider in the design of the house is how efficient it will be at holding the heat in. The R-values of the house should be at least R 18 in the walls and R 36 in the roof. More insulation can be used but cost increases as framework must become larger than structurally necessary to accommodate the added insulation. One possible exception to this flaw is the use of timber-frame construction and stretch skin panels as insulation outside the frames.

Regardless whether passive solar systems or a wood stove heats the house, the house must have an adequate thermal mass to hold the generated heat and radiate it back out into the space when needed. Good materials for thermal masses are masonry, brick, slate, concrete, adobe, and water. Wood stoves should be surrounded by a thermal mass

while passive solar systems should put a thermal mass in an area where it can be struck directly. Secondary and tertiary thermal masses not directly in the sun's path should be used to help stabilize the temperature of the house over the period of a week or during extremes of seasonal weather.

Lastly, a building must allow for heat to be transferred throughout the house. For this reason, airflow and circulation must be considered. Building convection loops into the layout of the house is one way in which to insure that heat can reach all areas of the house. An open story that allows heat to rise to the second floor and a well-placed staircase can accomplish this purpose. Other options include grates in the floor of all rooms; however, noise can become an issue.

Taking these suggestions into consideration can be a useful tool in the creation of a house that can minimize the energy required for space heating. Careful planning and design can produce a house where the majority of its energy comes from an inexpensive and sustainable resource.

ALTERNATIVE ENERGY SOURCES:

While most alternative homeowners are glad to give up their old furnace for a sunny southern exposure, few are willing to give up electricity. And, after all, why should they? Electricity, as a power source, has done more in the past century to raise the global standard of living than anything else. It is cheap, relatively simple to produce in most cases, and has an almost infinite number of uses. In terms of the alternative home, electricity is particularly good at creating light, cooling food, and pumping water. Unfortunately, the production of electricity is also directly responsible for a degraded

environment both in terms of resource extraction and air pollution. Not surprisingly, this issue puts the eco-minded homeowner in a tight situation. Is it possible, as the ancient proverb states, to have your cake (clean environment) and eat it too (electricity)?

Of course, the answer is both yes and no. On the one hand, it is impossible to create electricity without having an impact on the environment, but on the other hand it is quite easy to do better than we have been doing over the past several hundred years with fossil fuels. The answer lies in what is broadly termed, *alternative energy*. With respect to house design, this usually means electricity production through photovoltaic cells, wind turbines, or fuel cells. In the following section we will discuss each of these in some detail.

Photovoltaics: When people talk about solar panels they are usually referring to photovoltaics, or PV. The term *solar panel* has a much broader definition, and can refer to anything from solar hot water heating to PV electricity. In any case, PV is probably the most common means of producing alternative energy at the household level. At its most basic, a photovoltaic device, or silicon solar cell as it is sometimes called, converts light into DC (direct current) electricity. Here's how it works. When sunlight strikes a photovoltaic cell, the cell absorbs high-energy photons. In this process, electrons are knocked loose from the silicon atoms on the cell, leaving a series of "positive holes." The freed electrons and the positive holes together are neutral; therefore in order for electricity to be generated, the electrons and the holes must be separated from each other. To accomplish this, PV cells have an artificial junction layer called the *positive-negative layer* that stops the freed electrons from returning to their positively charged holes. However, when the electric contacts on the front and rear of the cell are run through an external

circuit, the freed electrons can return to the positively charged holes, and thus generate current! PV modules typically consist of forty cells, and produce somewhere in the neighborhood of fifty watts.

While all PV cells work in the same way, they are not all the same. There are two primary PV technologies in use today: crystalline and amorphous silicon. Crystalline silicon was developed for the space program in the early 1950's and has actually seen very little improvement in over 30 years. Crystalline silicon is grown in large blocks, and the thin wafers that become the solar cells are sliced off these blocks. The conversion efficiency of commercially marketed crystalline silicon is about 13%. While seems low, it is partially offset by the extremely long lifetime of silicon... solar cells from the 1950s are working nearly as well today as they did when they were produced!

Amorphous silicon, on the other hand, appears to be the wave of the future. It is made in a diffusion process where silicon material is vaporized and deposited onto a glass or stainless steel substrate. Because of this unique process, there are many possibilities for solar generation using amorphous silicon. Skylights, windows, roofing material, and sunroofs on vehicles are all potential electrical generators with this new technology. Amorphous silicon, unfortunately, at this point has a maximum of 6% conversion efficiency, requiring twice the surface area as crystalline silicon to produce the same amount of electricity. Additionally, thus far with research and development still in its adolescence, amorphous silicon has degraded significantly over time. However, amorphous silicon is much cheaper to produce than its crystalline counterpart, and will surely be brought up to speed in the near future.

Regardless of cell type, PV electricity can only work in locations receiving direct

sunlight most of the time. PV modules are useless in Alaska in winter and only moderately effective in New England, but are very effective in the southwest where it is almost never cloudy. Some PV systems have tracking arms that allow the modules to remain perpendicular to the sun's rays throughout the day. Rooftop PV modules can supply a modest household with enough electricity to live comfortably, however a backup generator is always recommended to compensate for long, cloudy stretches, times of peak demand and module repair.

Wind: A second popular alternative to PV electricity is wind power. The wind has been an important source of energy in the United States for 200 years, with over eight million mechanical windmills installed since the 1860s. Many of these units have remained in use for over a hundred years. Back around the turn of the century, before the REA began subsidizing rural electric chicken coops and power lines, farm families throughout the Midwest used 200-300 watt wind generators to power lights and household appliances. The modest wind industry that had built up by the 1930s was literally driven out of business by government policies favoring the construction of utility lines and fossil fuel power plants. Luckily, in the late 1970s and early 1980s interest was once again generated around wind energy as a possible solution to the energy crisis. As rural electrical consumers researched all the viable options, renewable energy alternatives, small wind turbines emerged as the most cost-effective technology capable of reducing their utility bills. Indeed, wind turbines remain popular today for the same reasons they were popular when they were first invented.

Most wind turbines are horizontal-axis propeller type systems consisting of a rotor,

a generator, a mainframe and a tail. The rotor captures the kinetic energy of the wind and converts it into rotary motion to drive the generator. The rotors are usually made of two or three wood or fiberglass blades, and, unlike old-fashioned windmills that could raise water from wells in even the slightest of breezes, must turn at a high rate to produce electricity. Generators, which are typically designed to work with particular rotors, are most often located immediately behind the rotor atop the wind tower. While people living in the mountains can sometimes mount wind turbines directly to their roofs, most homeowners opt for a 60 to 120 foot tower to put their generator more directly into the wind stream (Wind Power Basics).

Wind generators can be loosely classified into five categories, each of which corresponds to a specific load requirement. *Micro* and *mini* wind generators have rotors from .5 to 2.75 meters in length and can produce up to 850 watts of electricity. These can be used on houses, but would have to be supplemented with utility power or backup generator. *Household* wind generators have rotors from 2.75 to 7 meters in length and can produce up to 10 kilowatts of electricity, or enough to power boats, cabins, small farms and houses. Larger *industrial and utility* wind generators have rotors up to 90 meters in length and are used to power oil pumps, housing complexes and even to supplement grid power for large towns and cities.

While wind turbines are attractive for many reasons (they are cheaper than PV), they are not perfect. With many moving parts, they are far less reliable than PV modules, and they are site specific and oftentimes very noisy. In extreme winds (>100 mph), wind generators can even spin themselves out of control and effectively self-destruct if not equipped with an automatic braking mechanism. Nevertheless, wind generators have

supplied electricity to rural homeowners for hundreds of years and will undoubtedly continue to do so far into the future.

Fuel Cells: Most fuel cell research today is focused toward power for automobiles, however since this same technology can and will be used to supply household power in the future, we will include a section on it here. At their most basic, fuel cells are like batteries. However, unlike batteries they do not run down or require recharging; they produce energy in the form of electricity and heat as long as fuel is continually supplied.

Fuel cells are basically made of two electrodes sandwiched around an electrolyte. When oxygen, which enters through the cathode, passes over one electrode and hydrogen, which is fed into the anode, over the other, electricity, water and heat are generated. For this to happen, the hydrogen atom, encouraged by a catalyst, splits into a proton and an electron, which take different paths to the cathode. The proton passes through the electrolyte and the electrons create a separate current that can be utilized before they return to the cathode to be reunited with the hydrogen and oxygen in a molecule of water.

Most fuel cell systems include a *fuel reformer* that can utilize hydrogen from any hydrocarbon fuel - from natural gas to methanol, and even gasoline! Since fuel cells relies on chemistry and not combustion, emissions from the reaction are much less than emissions from the cleanest fuel combustion processes.

There are many different fuel cells both being developed and on the market today. Here is a brief description of each:

- **Phosphoric Acid:** This is the most commercially developed type of fuel cell. It is already being used in such diverse applications as hospitals, nursing homes, hotels, office buildings, schools and utility power plants. Phosphoric acid fuel cells generate electricity at more than 40% efficiency -- and nearly 85% if the steam produced is used for cogeneration -- compared to 30% for the most efficient internal combustion engine.
- **Proton Exchange Membrane:** These have high power density, can vary their output quickly to meet shifts in power demand, and are suited for applications where quick startup is required. According to the U.S. Department of Energy, "they are the primary candidates for light-duty vehicles, for buildings, and potentially for much smaller applications such as replacements for rechargeable batteries in video cameras"(Fuel Cells 2000).
- **Molten Carbonate:** Molten carbonate fuel cells promise high fuel-to-electricity efficiencies and the ability to consume coal-based fuels. They operate at about 1,200 degrees F, and have been researched and tested in California since 1996.
- **Solid Oxide:** These fuel cells may be the most promising since could be used in big, high-power applications including industrial and large-scale central electricity generating stations. A 100-kilowatt test is being readied in Europe, and two small, 25-kilowatt units are already online in Japan. This system uses a hard ceramic material instead of a liquid electrolyte, allowing generating efficiencies to reach 60%.
- **Alkaline:** These cells have been used by NASA on space missions, and can achieve power generating efficiencies of up to 70 percent. They use alkaline potassium hydroxide as the electrolyte. They have traditionally been too expensive for the common homeowner, but current research may soon help to bring the price down.
- **Other Fuel Cells:** Direct methanol fuel cells (DMFC) are a relatively new member of the fuel cell family. These cells are similar to the PEM cells in that they both use a polymer membrane as the electrolyte. However, in the DMFC, the anode catalyst itself

draws the hydrogen from the liquid methanol, eliminating the need for a fuel reformer. Efficiencies of about 40% are expected with this type of fuel cell, which would typically operate at a temperature between 120-190 degrees F. Higher efficiencies are achieved at higher temperatures. Regenerative fuel cells. Still a very young member of the fuel cell family, regenerative fuel cells would be attractive as a closed-loop form of power generation. Water is separated into hydrogen and oxygen by a solar-powered electrolyser. The hydrogen and oxygen are fed into the fuel cell which generates electricity, heat and water. The water is then recirculated back to the solar-powered electrolyser and the process begins again. NASA and others worldwide are currently researching these types of fuel cells (Fuel Cells 2000).

Although still primarily in the development stage, fuel cells could dramatically reduce urban air pollution, and in particular reduce the amount of carbon dioxide emitted each year. They fuel cell energy is so environmentally benign that it is sometimes called free energy, producing nothing but heat and water as a byproduct. The U.S. Department of Energy projects that if a mere 10% of automobiles nationwide were powered by fuel cells, air pollution would be cut by one million tons per year, and 60 million tons of carbon dioxide would stay out of the atmosphere. DOE projects that the same number of fuel cell cars would cut oil imports by 800,000 barrels a day -- about 13 percent of total imports. If this same reasoning can be applied to home heating and electricity, we could surely keep many times the pollutants out of the atmosphere.

CASE STUDIES:

Due to our increasing dependence on fossil fuels, some architects have designed energy-efficient homes in order to reduce the amount of energy used in the home. Homes designed to reduce dependence on energy generally utilize passive solar design and often

generate their own electricity through solar panels or wind turbines. One of the earlier houses designed to consume limited amounts of energy is the Burghardt House in Germany (Example 1). Built in 1979, it uses the basic principles of energy efficiency to cut down on energy use by 50%. The majority of the energy saved in this house is achieved through efficient space heating. The house is designed in a prismatic structure with the south-facing wall constructed entirely of glass. This forms the passive solar gain heating system that reduces the majority of the energy that houses use for space heating. There are also fewer windows on the north, east, and west walls. The windows that are present are constructed of insulating glass.

Wood was used extensively as a material to help insulate against heat loss. The limestone floors have also been reinforced with a thick layer of insulating material to prevent heat from escaping through the floor. Finally, overheating is avoided by a system of ventilation through the gable walls, and vents that are present to allow the entrance of cold air. Much of the building materials used were found locally to cut down on energy used for the transportation of materials (Mackenzie, 1991).

There have also been many houses built that generate their own electricity in addition to reducing energy use through a passive solar design. Peter Oxford's house in Cornwall, Vermont (Example 2) combines a passive solar design with creating his own wind energy, resulting in complete independence of local power lines. Oxford built the house himself in 1980 for roughly the same price that it would have cost him to build a traditional house. The 1,500 ft² house cost him approximately \$38,000, plus an additional \$13,000 for the wind generator. The house is designed in a basic saltbox shape along an east-west axis. The south side of the house is covered with windows and highly exposed to

the sun for heat. A thick cement wall makes up the north side of the house with very few small windows. It is protected from the wind and cold by trees. The only other source of heat for the long Vermont winters is a woodstove placed centrally in the house surrounded by thermal mass to trap and store its heat. Heat loss is also reduced by heavy insulation. Blueboard insulates the walls at an R-value of 18, while the roof is insulated with blueboard and fiberglass at R18. A slate floor that stays about 60 degrees Fahrenheit all year long also helps to maintain a constant temperature within the house. A 120-foot tall windmill supplies most of the house's energy needs at 1,500 watts. A back-up gasoline generator supplies any additional energy.

The Maine Solar House in Cape Porpoise, Maine (Example 3) also combines passive solar design with creating its own energy; however, it does not compromise lifestyle. Unlike Oxford's house, the Maine Solar House uses the newest technologies and designs to create a highly efficient, but also costly, home. This energy-efficient home accommodates regular energy needs. The house is 2,900 ft² in total; the downstairs has a large great room, kitchen, dining room, and master bedroom, and the upstairs has two bedrooms, a study, and storage space.

The south-facing roof is covered with solar thermal panels for hot water and space heating and photovoltaic panels for generating electricity. The solar thermal panels allow water to be circulated in the roof where it is heated by the sun and then stored in two 500-gallon tanks in the basement. Two pumps pump water upwards to the roof. This water heating system even works on most cloudy days, but a propane heater exists as backup. The other half of the roof is used to create electricity. Sixteen 4' x 6' panels provide 4200 watts of power. The Maine Solar House uses 90% less fuel than a conventional house and

90% less electricity. In 1999, the house harvested 4,508 kWh of power from the sun, which included a surplus of 352 kWh.

William Lord, the owner of the Maine Solar House, admits that the house was costly to build. The energy system cost him about \$40,000, and he estimated that it would take about 12 years to pay back the thermal solar component and 22-25 years for the PV system. The house in total cost him \$300,000 to build. Lord, however, is proud to be a home owner that does not add to Earth's pollution, but rather uses the sun to create clean energy (Solarhouse, 2000).

In more recent years, less traditional energy efficient houses are being designed as well. The Earth Sweet Home in Dummerton, Vermont (Example 4) is an experimental house built by a non-profit organization to explore the advantages and capabilities of a sustainable house. The house is built entirely of local straw, wood, and stone. All the materials used in the foundation, frame, roof, walls, and interior were extracted from within 30 miles of the building site. There is only a limited amount of synthetic materials and other energy intensive materials. The house's frame is made of wood and it is wrapped with straw bales to a thickness of 18" before plastering. The straw bale walls are an excellent insulator at R45 and are used throughout the walls. An extremely thick amount of straw bale is also used above the ceiling, which is insulated to at least R60. A recycled cotton insulator with R30 was used between the basement and first floor. Old stonewalls from the property were recycled into the house's foundation, which is over 2' wide. The roof overhangs all four sides and is shingled with cedar and covered with vents to keep the roof cool and free of ice dams (Earth Sweet Home, 2000).

The Earth Sweet Home also maximizes solar gain with the long sides of the house

facing north and south; there are very few windows on the north side and numerous windows on the south. Windows on the east and west are crucial for cross ventilation in the hot summer months. All windows are made of triple-glazed high efficiency glass with insulation. All electricity used by the home is created on-site with a wind turbine and solar panels (Earth Sweet Home, 2000).

Even more radical than the Earth Sweet Home are the sustainable houses known as Earthships (Example 5). These homes are made out of used tires and tin cans as building materials. The main load-bearing walls are built by filling old tires with earth and laying them like giant bricks. The thick walls create a strong thermal mass to help maintain the temperature inside the Earthship at a comfortable 60-70 degrees without the use of other heating or cooling systems. The non load-bearing walls are constructed from tin cans and cement then covered with mud, plaster, or stucco. Earthships also use passive solar design to create heat. The North, East, and West walls are built out of the thick tire walls, while the south wall is made up of windows and is slightly angled. The angle increases the amount of sun received in the winter and minimizes summer sun to prevent excessive heat gain. Earthships can be built almost anywhere, as the building materials are cheap and easy to find, and the basic design can be adapted to almost any environment. Many of the Earthships are coupled with either active solar panels or wind generators for complete “off-the-grid” living. Earthships claim to be “more than just innovative ways to build with our old ‘garbage.’ Earthships are a new approach to living that involves interfacing with the Earth – peacefully coexisting and thriving in nature” (Earthships, 2000).

WEYBRIDGE HOUSE TODAY:

Currently, Weybridge is the academic interest house of the environmental studies department. It houses 17 students during the school year, and 12 Breadloaf students during the summer. The current structure is a three story Victorian house with clapboard siding and an asphalt-shingled roof on the corner of Weybridge St. and Route 125 in Middlebury, VT. It is 4,500 square feet, with 5 single and 6 double rooms, a kitchen, a living room, a library, three bathrooms and a basement. The Weybridge House consumes an average of 1,291 kilowatt hours of electricity per month, 2,042 cubic feet of water per month, and 2,369 gallons of heating fuel per year. As of now, this building has virtually no southern exposure and does not benefit from passive solar.

HOLISTIC THINKING:

When designing a house, the decision-making process must go beyond the information found in a book and incorporate serious consideration of the land on which it is to be built as well. Jumping into the planning process with preconceived notions or prefabricated designs will not result in the highest level of sustainability possible. Rather, one must be conscious of the natural landscape and work *with*, instead of *against*, it. As we began our design process, we tried to keep these principles in mind. After researching information about various house systems, we applied this knowledge to the specific site on which we propose building in order to arrive at an integrated, appropriate, and feasible model.

OUR HOUSE:

We have chosen to build the house on Porter Field Road, adjacent to Porter House where the greenhouse now stands. The advantages of this site includes: expansive exposure to the south, lack of obstructing objects, and protection from northerly winds by Porter House and a stand of coniferous trees. These coniferous trees maintain their foliage and protect from winds year round. This site is located on the periphery of the Middlebury College campus, making it suitable for the placement of windmills.

The total square footage of the house is 7,818 sq. ft. of usable floor space. We designed the building to house 19 individuals, one of whom is the Resident Advisor. The students living quarters include two singles, one triple, and seven doubles. The house contains two bathrooms with four toilets, six showers, and six sinks. More specifically, the first floor of the house includes: one single, one double, a bathroom, a large open area on the first floor containing the kitchen, dining room, and living room; a pantry, and a mudroom. The second floor consists of one single, six doubles, a bathroom, and two utility closets. The third floor contains one triple, a library, battery bank, and storage area.

The construction of the house follows a post and beam structure. The post and beams will consist of recycled material from deconstructed local structures, such as barns. The exterior walls are made of shiplapped vertical siding made up of locally cultivated wood. This exterior siding on the north wall abuts a 14-inch brick thermal mass, while the exterior of the east- and west-facing walls covers underlying stretch skin panels topped with plywood. The remaining south-facing wall is comprised entirely of double glazed windows. The roof consists of slate tiles, in keeping with the tradition of the Middlebury College campus architectural style. Solar panels, however, occupy a majority of the south-facing portion of the roof.

A shed attached to the house protects the sole entrance to the structure from outside weather. Wood will be piled inside the shed for use in the wood stoves. In addition, the shed will serve as a storage area for tools and a backup generator.

The mudroom functions as an airlock between the core of the house and the outside. Two doors on either side remain closed and prevent cold winds from penetrating, cutting down on heat loss. Furthermore, the mudroom provides a place to hang coats and remove shoes and boots. Adjacent to the mudroom lies the utility room, which houses the water heaters.

The mudroom leads into the kitchen, which includes a center island constructed of a brick base topped by a wood countertop, along with a built-in sink. A three-and-a-half foot tall wood countertop also lines the back wall, which runs along the north side of the house. The countertop contains another sink and a six-burner gas stove, designed to meet the needs of cooking for the 19 inhabitants. The wood countertop continues along the east wall, which also houses an energy-efficient electric-powered refrigerator, separate freezer, and entrance into the pantry. Finally, the continuous wood countertop divides the kitchen from the dining area, accompanied by wood stools.

The pantry extends off of the kitchen, and functions as a storage area filled with shelves and cabinets for stocking non-perishable food products, as well as housing an additional propane-fired refrigerator and freezer. This pantry lines the north side of the house and is isolated from direct sunlight, resulting in a cool environment ideal for food storage.

The dining and living areas contain 3 tables for dining, composed of a brick base topped by wood, along with couches and chairs for recreation and lounging. The south

wall is consists wholly of glass, providing ample natural light. Finally, the floors are made of slate, as is the entire first floor.

The second and floors are comprised in large majority of individual rooms. Each room contains a bed, closet, and desk for each inhabitant. Selected rooms contain brick thermal mass along one wall to aid in heating. In addition, on the third floor, there is a library. The library is lined with bookshelves and also houses three wooden tables to provide a study area for the students.

The choice of building materials utilized in the construction of the home reflect conscious decisions intended to lessen the environmental impact of the house. For example, we selected brick for use as a thermal mass rather than concrete. As noted earlier, the energy demands for concrete production are massive due to cement, an integral component of concrete that requires on average 6 million BTUs per ton of cement (Steele, 1997). These energy requirements are met through the use of fossil fuels. 60.8% of the energy is generated through the burning of coal (Steele, 1997), releasing CO₂ that contributes to global warming.

Brick production also requires a large amount of energy, consumed mainly in kiln heating. However, these energy demands can be reduced through the use of efficient kilns that recycle heat and minimize heat loss. Moreover, brick shares the advantages of concrete in that it provides a high thermal mass for passive solar design and is durable and fire-resistant.

The slate floor on the first level of the house was chosen for its value as a thermal mass that traps and releases heat and regulates floor temperature. This material is durable, long lasting, and recyclable. Slate is a nonrenewable resource, however; therefore, we

intend to pursue efforts to acquire recycled slate if possible.

Timber is arguably the most sustainable building material available. For this reason, we chose to use it for our exterior shell and post and beam structural support. As mentioned earlier, recycled posts and beams are readily available locally. Timber is a great insulator, along with being recyclable, biodegradable, strong, long lasting and self-sufficient, and thus serves our needs in an excellent manner.

The heating system for our house is an amalgamation of passive solar design components. The direct gain system relies on 982 square feet of double glazed south-facing windows to heat the space and the thermal masses situated in the floor, walls, and hearths. The square footage of these windows rests at the mid- to upper-range of the amount of exposure needed to heat the first floor thermal mass. The suggested window-to-floor thermal mass area ratio is between 0.19 and 0.38 in a climate such as that found in Middlebury (Mazria, 1979). The ratio found in our building is 0.29. The horizontal angle of the south wall maximizes the amount of winter sunlight while minimizing the amount of summer sunlight.

The sun entering through these windows strikes directly upon a slate thermal mass which covers the first floor of the house. Also acting as secondary thermal masses for the stabilization of house temperatures over a period of days is the 3 1/2ft brick wall dividing the kitchen from the living area, the full brick wall that divides the pantry from the living area, and the large brick hearths on either side of first floor living space on which the two wood stoves rest. In addition, a 14-inch thick thermal mass stretches the length of the north wall to provide temperature stabilization over periods of extreme weather. The thickness of these thermal masses was sized using formulas provided by Mazria (1979).

As a means of auxiliary heat, our house has two wood stoves. Each wood stove rests on an ample amount of brick hearth, which acts as a thermal mass. Heat from the firing of these stoves will not only heat the air directly, but it will also be transferred into the brick thermal mass to be stored until room temperatures drop during the night.

Our house is insulated using stretch skin panels in the walls and roof. These panels provide an R-value of 18 in the walls and 30 in the roof. These values are in line with suggested R-values for well-insulated houses outlined in Metz (1981).

Numerous elements of our house's design cut down on heat loss. The salt box shape of our house provides for a large amount of southern exposure while minimizing the amount of northern exposure. The east/west axis of our house also maximizes the amount of surface area that can be devoted towards southern facing windows. The rectilinear shape of our house consolidates the spaces that need to be heated by reducing the surface-to-volume ratio. Finally, no part of the home juts out in isolation from the heat source. This allows for easy heat transfer throughout the house.

The open story found on all three floors sets up a convection loop with the staircases that allows for heat to be transferred to all levels of the buildings. Heat rises through this open story to the second and third floors. Cold air can descend through the central staircase leading down from the third to second floor. From there, it can move out along the north wall to either the east or west staircase where it can descend to the first floor to be reheated by the passive solar system or the auxiliary wood stoves. Windows in each of the second floor doubles looking out onto the living area allow for heat to be transferred from the open story into the individual rooms, provided they are left open.

In addition to providing for the transfer of heat, the open story allows for a

communal feeling to pervade throughout the house. Residents can look out from their rooms onto the living area below. At all times, they can feel connected to the way of life and community living in the house. However, during times of privacy, they can also pull curtains across these windows.

The brick chimneys on the east and the west side of the house each abut on the walls of the rooms separated from the living space. These chimneys can therefore transfer heat to the east and west rooms of the house on all three floors as well as to the open living area.

The choice of a passive solar heating system also influenced the design of our housing in other ways. The living area is placed on the southern side of the house because this is the warmest and most pleasant area with sunlight entering in. We reserved the northern side of the house for uses that did not require as much heat such as the second story hall way, stair cases, and the battery storage on the third floor. Curtains can be drawn across the expansive area of southern glass during the night to conserve heat. These curtains can also be drawn to prevent unwanted sunlight during the summer.

The new environmental house will use a combination of photovoltaic and wind generated electricity. We will implement both technologies both since Middlebury is neither sunny nor windy all of the time, and because we feel this house should serve as an environmental teaching station with a variety of working technologies. The 35 photovoltaic modules (see calculations below) will measure 37" x 16," produce 50 watts at 73° F each, and be mounted to the southern roof. The five wind generators will be 100 feet tall and each produce 50 watts of electricity with a 12 mph wind speed, accounting for over half of the total power supply. This may seem like a large number of wind generators for a

single house, but we feel that wind is a cheaper and more reliable source of power in a state that averages only four hours of sunlight per day. Of course, electricity will be stored in a bank of 42 deep-cycle batteries. Most of this stored power will run direct (DC) to the house lights, refrigerators and freezers, and the rest will be inverted to AC to accommodate appliances such as clocks and radios. A single propane backup generator will live in the attached woodshed, and be used during extended calm, cloudy periods.

Table 1: System demand planning chart

Appliance	Quantity		Wattage		Hrs/Day		Ave. Watt-hrs/day
Refrigerator	1	x	150	x	9	=	1,350
Freezer	1	x	226	x	8	=	1,808
Lights	40	x	15	x	4	=	2,400
Misc.	19 (students)	x	25	x	5	=	2,375
					TOTAL	=	7,933
Total watt-hour/day			Battery Inefficiency Factor			Total Corrected Watt-hours/day	
7933		x	1.25		=	9,916	

Table 2: Wind Power Supply

Average Windspeed at Site	12 mph
Wattage at this windspeed	50 watts
Hours running	X 24
Expected Watt-hours/day	= 1,200

NOTE: Since our total energy requirement is 9,916 watt-hours/day and one wind generator can produce 1,200 watt-hours/day, we have chosen to use five *household* sized wind generators to produce 6,000 watt-hours/day. This leaves 3,916 watt-hours to be provided by photovoltaic.

Table 3: Photovoltaic supply

Total Corrected Watt-Hours/day	3,916 (for solar only)
Hours of Sun per Day	4
Minimum Array Wattage Subtotal	= 979
Photovoltaic Derate Factor	X 1.15
Array Wattage Total	1,125
Watts per module	50
Number of modules required	= 23

Table 4: Battery sizing chart

Total Corrected Watt-Hours/day	9,916
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System voltage	$\times 12$
Load amp-hours per day	$= 826$
Days of storage	$\times 4$
Amp-hours battery storage capacity	$= 3,304$
Maximum depth of discharge	$\times .8$
Total battery capacity	$= 4,130 \text{ Ah at 12 volts}$
Amp-hours per battery	$\times .100$
Total batteries needed	$= 42$

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